NASA-CR-202243



A progress report for

80948

# THE SOLAR SYSTEM BEYOND NEPTUNE

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## Goals

The aim of this research is to assess the contents of the trans-Neptunian solar system. Previously thought to be empty, the region beyond Neptune is now known to hold a vast abundance of bodies dating from the earliest phases of the solar system. We have pioneered the application of charge coupled device (CCD) surveys as a means to locate and identify Kuiper Belt objects. The present research aims to drive these techniques to their limit, in order to increase the observational sample as much as possible.

## Accomplishments

In the first year of this grant we have done the following:

1 We completed the MKCT Survey (Jewitt, Luu and Chen 1996). This is a survey of 4 sq. deg. to limiting red magnitude $m_R = 24.2$. The survey has a number of surprising results.

First, the sky-plane surface density of Kuiper Belt objects reaches S = 1 deg$^{-2}$ at $m_R = 23$. The total number of objects larger than 100 km in diameter is 70,000, in the distance range 30 to 50 AU.

Second, the differential size distribution in the 100 km to 400 km diameter range is compatible with $n(D)\,dD = \Gamma D^{-q}\,dD$, with $\Gamma$ = constant and $q = 3$. The mass of bodies implied by this distribution is of order 0.1 $M_{Earth}$.

Third, about 35% of the trans-Neptunian objects fall in or near the 3:2 mean motion resonance with Neptune (a total of 30,000 objects with diameter ≥ 100 km). These objects are dynamical siblings of Pluto, which also occupies the 3:2 resonance (see Figure 1). All these "Plutinos" are protected from close encounters with Neptune by the resonance. We have already identified 4 examples of Plutinos which mimic Pluto in that their perihelia fall inside the orbit of Neptune.

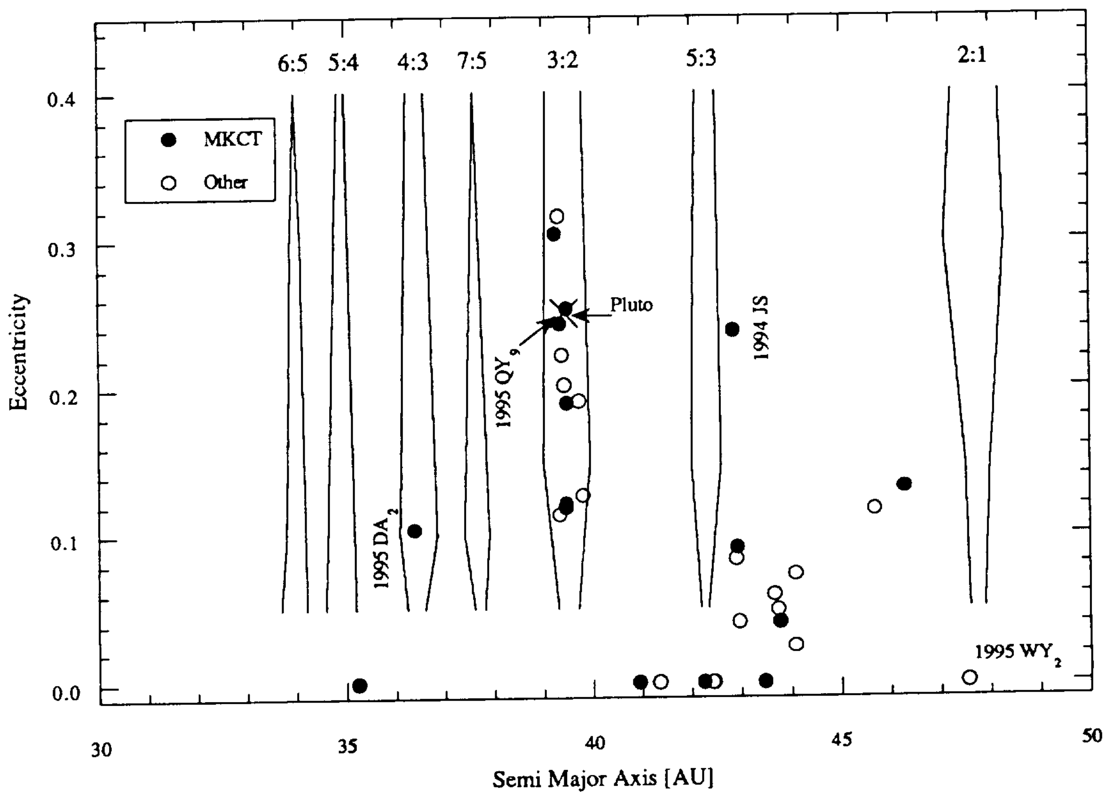


Fig. 1 Semimajor axis vs. eccentricity for the known Kuiper Belt objects. The plot shows objects from the MKCT survey (filled circles, JLC96), and other surveys (empty circles). The location of the major mean-motion resonances are marked and labelled. Pluto, also in the 3:2 resonance, is marked with an X. Figure from JLC96.

Fourth, we modelled our survey data to constrain the inclination distribution in the Kuiper Belt. This is a fundamental quantity in connection with the hypothesized dynamical route from the Belt to the short-period comets. We found that the existing data prove only that the width of the

Kuiper Belt is very large, with a FWHM of at least 30° (JLC 96). The actual width is not well constrained by the available data, because of the overwhelming effects of observational bias against high inclination objects.

Fifth, we made the first quantitative estimate of the surface density of Centaurs based on our MKCT data. Centaurs are objects orbiting between Jupiter and Neptune. Because of perturbations by these planets, the Centaurs have dynamical lifetimes of only a few million years, and must therefore be continually resupplied from another source. The most plausible source is the Kuiper Belt itself, in which case the Centaurs may be viewed as objects in transition from the Belt to the inner planetary region. Our data show that Centaurs are over-abundant with respect to the only published prediction by about a factor of 50. The cause of the over-abundance is unclear.

2 We have developed a software and operating strategy to handle data from the University of Hawaii 8192 x 8192 pixel CCD camera. This is the largest camera in use in the astronomical world. It presents unprecedented problems in data handling and storage, when used in survey mode. We plan to use the 8k array to advance our surveys of the trans-Neptunian solar system. With graduate student Chadwick Trujillo, we have arrived at a system for the nearly automatic detection of moving objects in survey data. This system was tested on Mauna Kea in May 1996, and several problems were resolved by reprogramming on the mountain. The 8k CCD is still a frighteningly productive instrument to use, but we are confident that we can use it to detect Kuiper Belt objects at high efficiency.

3 It is important to obtain follow-up astrometry of newly discovered Kuiper Belt objects, in order to determine their orbital elements with confidence. We have occasionally been thwarted in this by weather and instrument problems, resulting in the loss of some of the 36 known Kuiper Belt objects. Nevertheless, we have made a substantial observational effort to recover Kuiper Belt objects, and have been responsible for a majority of the follow-up astrometric observations obtained to date.

4 We wrote a popular-level account of our Kuiper Belt endeavors for Scientific American

magazine (Luu and Jewitt 1996). We were invited to write another for American Scientist, and have started work on this.

5 The PI was invited to speak about his Kuiper Belt research at the Asteroids, Comets, Meteors '96 meeting in Versailles, France, the Stardust Symposium in Santa Clara, Ca., and at several universities. Reviews for the Versailles and Stardust meetings are in preparation.

**Plans for Year 2**

1 With the 8k CCD now ready to be used for trans-Neptunian surveys, we have applied for and obtained telescope time to begin a new survey. In this, we intend to cover 50 sq. deg. to magnitude 22.5, and expected to detect several 10's of new Kuiper Belt objects. The science goals of this survey build on questions raised by MKCT. Specifically,

i) Current data suggest the existence of a turn-down in the size distribution of Kuiper Belt objects at large sizes ($D \geq 600$ km?). However, the evidence for the turn-down is largely based on old photographic data. With the 8k CCD, we will for the first time cover a large area of sky to moderate depth in order to assess the density of large (bright) objects.

ii) Is the factor of 50 over-abundance of Centaurs detected at faint levels in MKCT present at all body sizes? The new survey will address this question directly by revealing Centaurs in the distance range $5 < R < 30$ AU.

iii) Do Trojans (1:1 mean motion resonance objects) exist in association with gas giant planets other than Jupiter? The Jovian trojans are well known and abundant, and there is no known theoretical reason why other gas giants should not also hold Trojans, yet none have been found. We will survey for Trojans automatically, by selecting Kuiper Belt fields which fall along lines of site passing through the 1:1 libration clouds.

2 We will determine the width of the Kuiper Belt using new observations taken at high ecliptic latitude. To date, our fields have all been chosen in the ecliptic, maximizing the number of detected objects but rendering the empirical inclination distribution vulnerable to observational bias against

high inclination orbits. The new geometry to be employed should reveal the Belt thickness for the first time. This quantity controls the collisional regime in the Belt (e.g. erosive vs. agglomerative collisions) and is a constraint on theories which aim to explain the orbital properties of some Belt objects by means of pumping at resonances.

3 We will obtain physical data on the Centaurs and Kuiper Belt objects. Physical observations are extremely challenging, because the Kuiper Belt objects are distant and faint. Accordingly, we have secured time on the Keck 10 meter telescope in order to obtain optical-near IR photometry of Kuiper Belt objects. This photometry will be used to examine the distribution of surface types in the outer solar system. We are especially interested to understand how the very different surfaces of Centaurs 2060 Chiron and 5145 Pholus can be produced, and want to know whether this spectral diversity extends throughout the Kuiper Belt.

4 We will continue to obtain follow-up astrometry of Kuiper Belt objects, for the purposes of orbit refinement. Data collected for this purpose will be provided to Brian Marsden at the Center for Astrophysics, Harvard, and publicized through the Minor Planet Electronic Circulars.

This research will continue to benefit from the collaborative efforts of Prof. Jane Luu (Harvard University) as well as UH graduate students Jun Chen and Chad Trujillo. Jun Chen is writing her PhD thesis on this subject and Chad Trujillo has expressed interest in starting a thesis.

**Publications**

J. Luu and D. Jewitt (1996). The Kuiper Belt. Scientific American, May 1996 issue (pp. 48-55).

D. Jewitt, J. Luu and J. Chen (1996). The Mauna-Kea Cerro-Tololo (MKCT) Kuiper Belt and Centaur Survey, Astron. J., 112, 1225-1238.

J. Luu and D. Jewitt (1996). Color Diversity Among the Centaurs and Kuiper Belt Objects, Astron. J., in press.